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Rasmussen, Torben Valdbjørn

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BUILDINGS DESIGNED WITH AN ENERGY-EFFICIENT BUILDING ENVELOPE

Torben Valdbjørn Rasmussen MSc. CivEng, PhD

Danish Building Research Institute, Aalborg University, Department of Building Design and Technology, Dr. Neergaards Vej 15, DK-2970 Hørsholm, Denmark, tvr@sbi.dk, http://www.sbi.dk

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Summary

In buildings the largest and most cost-effective potential for energy savings lies in reducing energy consumption. Reducing energy consumption in buildings for heating and comfort will lead to more sustainable buildings. Methods for reducing the energy consumption in buildings by reducing heat loss through the thermal envelope were discussed. In particular air tightening of the building envelope and superinsulated building components. Principles for air tightening of the building envelope were discussed and new principles for making superinsulated strip foundation of prefabricated lightweight elements were introduced and demonstrated as an alternative to strip foundation of concrete as traditionally used. The prefabricated elements, made of expanded polystyrene, were designed to be handled on site by one man. An area of non-freezing ground was established by using outer insulation located at the outer plinth. The element was integrated into the insulation located underneath the concrete floor slab, constructing a foundation system that allows very little energy to be lost through the joint that connects the concrete floor slab with the outer wall. The strip foundation allows for a full and continuous insulation cover against the heated part of the building.

1. Focus (2008)

The new Danish Building Regulations (Danish Enterprise and Construction Authority 2008) will have an impact on energy consumption in buildings, in that the regulations focus on the thermal envelope as well as individual building components. The aim is to reduce energy consumption for heating and comfort and that this will lead to more sustainable buildings. The new Danish Building Regulations entered into force on 1 February 2008.

One focus area was heat loss through the thermal envelope, in particular methods that ensure air tightening of the building envelope, eliminating thermal bridges and innovation of individual building components.

The new Building Regulations are part of a major action plan presented in 2005 by the Danish Government. The action plan aimed to promote significant results in the energy field. This action plan will have an impact on Danish energy-saving initiatives in years to come (Ministry of Transport 2005). The action plan includes a description of the Danish energy sector in the years leading up to 2025. One strategy of the action plan is the climate policy related to the Kyoto Protocol, United Nations (1998), which entered into force on 16 February 2005. As part of the internal distribution of obligations within the EU, Denmark must reduce its emissions of greenhouse gases by 21% compared with 1990 (Olesen, et al. 2004).

The action plan focuses on energy consumption in buildings, where the largest and most cost-effective potential for energy savings lies. The most important initiative is the tightening of the energy provisions in the new Danish Building Regulations.

The tightening of the energy provisions paves the way for further strengthening in 2010 and in 2015. The tightened energy provisions will result in an energy reduction of 25% for new buildings compared with buildings built in accordance with the former Building Regulations (Danish Enterprise and Construction Authority 1995).

2. Heat Loss through Leakages in the Building Envelope

Air tightness is an important property of building envelopes. It is a key factor for determining infiltration and related wall performance properties such as heat loss, indoor air quality, maintainability and moisture balance. Air leakage through the building envelope contributes to ventilation, heating and cooling costs and moisture migration. Air tightness is the property of building envelopes that is most important for understanding ventilation. It is quantified in a variety of ways, all of which typically go under the heading of “air leakage”. Air tightness is important from a variety of perspectives, but most of them relate to the fact that air tightness is the fundamental building property that impacts infiltration. There are a variety of definitions of infiltration, but fundamentally infiltration is the movement of air through leaks, cracks, or other unforeseen openings in the building envelope.

There is a direct connection between an airtight building envelope and a low consumption of energy in the building. In the North European countries, where outdoor air that seeps in through unforeseen leakages in the building envelope, infiltration increases the energy consumption for heating. It is estimated that infiltration increases the energy consumption by 20 to 30% compared with an airtight building envelope (Valdbjørn Rasmussen and Nicolajsen 2007). With regard to a better heat–insulated thermal envelope, the importance of an airtight building envelope becomes more pronounced in relation to the total energy consumption of the building. Furthermore, infiltration in the building envelope will result in both a less efficient heat exchanger if used for the ventilation system of the building and an increased risk of mould growth within the building envelope. However, a building must be ventilated. Fresh air should be provided to the building in an energy-efficient way that satisfies human needs for hygiene and comfort.

2.1 Air tightening of the building envelope

An airtight shell defined as that shell which encases the heated interior of a building and prevents infiltration in the thermal envelope is introduced, see figure 1.

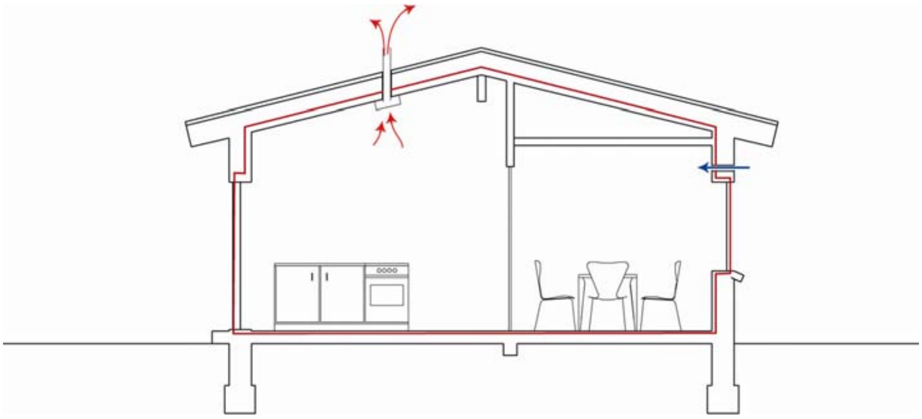

Figure 1 Location of the airtight shell in a building. The shell follows the building envelope, which consists of lightweight or heavy weight building components like wood-stud walls and concrete wall elements, respectively, combined with windows, doors, ceiling, roof and floor-slab constructions.

Typically the airtight shell follows the building envelope that consists of lightweight or heavy weight building components like wood-stud walls and concrete wall elements, respectively, combined with windows, doors, ceiling, roof and floor-slab constructions. Critical locations in the shell are located where building components are located in staggered levels, in joints between building components and at ductways, where installations are brought into the building. For lightweight building components such as wood-stud walls and ceilings, the airtight shell can be established by a 0.15 to 0.2 mm polyethylene foil additionally serving as the vapor barrier located within the insulation layer, e.g. placed between the wood trusses and the laths, see Figure 2. When the foil is used as a vapor barrier as well as an airtight shell, it is crucial that the foil is located at the warm side of the dew point and that the joints between the sheets of foils and joints facing other building components are securely fixed and airtight. Furthermore it is crucial that the joints keep their airtight properties during the lifetime of the construction, and are not damaged or decomposed during their service life. This entails a great deal of focus on how to establish the airtight shell on site during the design phase.

When preventing infiltration of the building envelope, a more efficient heat exchanger can be established, if used for the ventilation system of the building. A building should be ventilated to provide the building with fresh air to satisfy human needs for an indoor climate with a good hygiene and good comfort. When designing the ventilation system of a building, indoor air is primarily removed from rooms producing moisture and pollution from indoor activities, including rooms such as kitchens, utility rooms, bathrooms etc. Outdoor air supply is provided to living rooms and residential areas. The ventilation should not cause air velocities that locally exceed 0.15 m/s, which is normally considered to be the limit when humans feel a draft from airflow. Figure 2 shows a vent for ventilation mounted in the ceiling. The airtight shell was located in the ceiling and the vent was built into the shell. The vent was fixed to a wood support attached to the wooden trusses. The vent itself should be airtight and attached airtight to the airtight shell of the entire ceiling. The airtight shell of the ceiling was established by a polyethylene foil that also served as a vapor barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was mounted on the frame of the vent and joint. The joint was secured and fixed in a way that ensured that it would perform and stay airtight during its service life.

Figure 3 shows a hatch for passage to the loft through the ceiling. Where the airtight shell was located within the ceiling, a hatch was mounted in the ceiling so it was built into the airtight shell. The hatch itself was airtight and the airtight shell of the hatch was extended to the airtight shell of the entire ceiling. By using a polyethylene foil as the airtight shell in the ceiling, the foil had to be securely attached to the frame of the hatch. A packing between the opening part of the hatch and the frame of the hatch ensured that the hatch was airtight when it was closed.

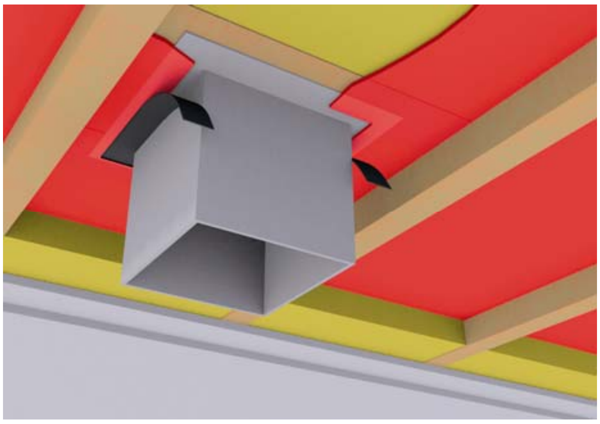

Figure 2 Ceiling-mounted vent for ventilation. The figure shows in detail how the airtight shell of the entire ceiling was attached to the vent. The airtight shell in the ceiling was established by a polyethylene foil, additionally serving as the vapor barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was joined to the frame of the vent. The joint was secured and fixed in a way that ensured that it would perform and stay airtight during its service life.

Infiltration in the airtight shell was located by creating a pressure difference between the interior and the exterior of the building. By maintaining a pressure difference, infiltration would be revealed when designed openings in the building envelope were closed. Having lower outside temperatures compared with the temperature inside the building, infiltration was easily revealed by maintaining a low pressure inside and using thermograph equipment.

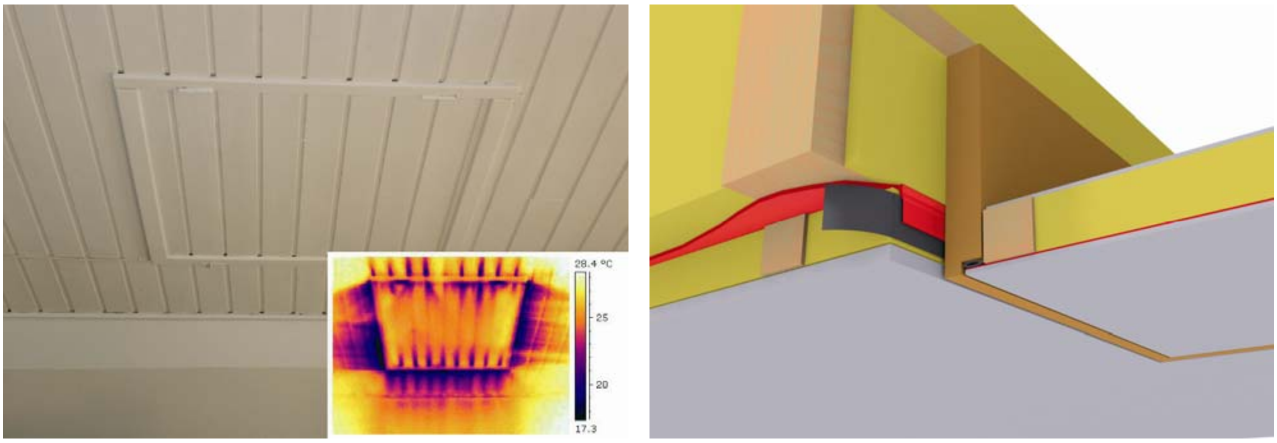

Figure 3 Ceiling with a hatch. The picture to the left shows an ordinary photo of a ceiling with a thermographich picture inserted at the lower right corner. The thermographic picture shows the infrared thermographic observation of a ceiling with a hatch. The colors on the infrared thermographic picture visualize the temperature of the ceiling. To the right, the figure shows in detailed how the airtight shell of the hatch was extended correctly to the airtight shell of the entire ceiling. The airtight shell in the ceiling was established by a polyethylene foil that also served as a vapor barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was joined to the frame of the hatch. The joint was secured and fixed in a way that would ensure that it stayed airtight during its service life.

Thermograph equipment was used to show surface temperatures. Low temperatures inside a building reveal thermal bridges or locations of infiltration where cold air was sucked in when a low pressure was created inside. An infrared thermographic observation of a ceiling with a hatch is shown in Figure 3. The colors on the infrared thermographic picture visualize the temperature of the ceiling. The pictures to the left show an ordinary photo of the ceiling with the thermographic picture inserted at the lower right corner. To the right, the figure shows in detail how the airtight shell of the hatch was extended correctly to the airtight shell of the entire ceiling when fixed. The airtight shell in the ceiling was established by a polyethylene foil, additionally serving as the vapor barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was mounted on the frame of the hatch and joint. The joint in particular was secured and fixed in a way that would ensure that it stayed airtight during its service life.

Heavy-weight building components such as concrete wall elements should themselves be airtight as well as being able to joint airtight for use in and as the airtight shell. Guidelines for establishing an airtight shell are given in Valdbjørn Rasmussen and Nicolajsen (2007).

2.2 Heat Loss through Thermal Bridges in the Building Envelope

A thermal bridge is defined as that a part of the building envelope where otherwise uniform thermal resistance is significantly changed. Typically by a full or partial penetration of the building envelope by materials with a different thermal conductivity, or by a change in thickness, discontinuation of the insulation material e.g. at wall, floor and ceiling joints. Typically such thermal bridges occur at the joints of different building components where it is difficult to achieve continuity in the thermal insulation layer. Thermal bridges give rise to two- or three-dimensional heat flows and have a major effect on the thermal performance of the building envelope. Thermal bridges decrease the internal surface temperature locally, thereby increasing the risk of mould growth at high humidity levels (Valdbjørn Rasmussen et al. 2006). The better the insulation of the building envelope, the larger the relative contributions of thermal bridges to the overall transmission heat loss of the building, and the more important it is to develop improved constructional details as well as improved buildings components. The effect of thermal bridges in the building envelope is significant, either due to the long length of joints per unit of the heat loss surface or due to joints with large thermal transmittance. It is estimated that thermal bridges in the building envelope increase the energy consumption by 13 to 17% compared with a continued homogenously insulated building. When attention is paid to avoiding thermal bridges in construction detailing, the contribution of building joints to the thermal transmittance may be minimized to less than 5% of the heat loss (Janssens et al. 2007). In low energy building design, this quality of detailing is certainly necessary to obtain a sufficiently low average thermal transmittance of the overall building envelope.

One focus area has been heat loss through the strip foundation of a building. In order to improve the joint between the exterior wall and the floor slab, a new solution was introduced as an alternative to the traditional Danish strip foundation of concrete. The new solution was a prefabricated lightweight element intended to meet the same performance requirements as the ones traditionally used.

2.2.1 Superinsulated strip foundation elements

The prefabricated elements were made of expanded polystyrene to form an element that could be used as the strip foundation of a house up to two storeys high. Elements were produced as one coherently shaped element through a production including an injection-molding process. The expanded polystyrene is produced from a mixture of about 5-10% gaseous blowing agent (most often pentane or carbon dioxide) and 90-95% polystyrene by weight. The solid plastic is expanded into a foam through the use of heat, usually from steam. The voids filled with trapped air give the element a low thermal conductivity. This makes it ideal as a construction material used as insulation in building systems. In the following the expanded polystyrene will be referred to as EPS. The calculated thermal conductance is 0.034 W/mK. The prefabricated element was specially designed to form the base for a house with an exterior wall of either a traditional double-brick wall, a traditional wood-stud wall, or combinations of lightweight concrete, brick and wood-stud walls with insulation. However, only when the strip foundation was fully integrated into the insulation located underneath the house, a foundation system was created that allowed very little energy to be lost through the foundation element that connected the concrete floor slab and the outer wall. In this case the strip foundation was to form the base for a house with an exterior wall made as a traditional wood-stud wall within insulation. The prefabricated EPS element was produced as units of 1.2 m in length and 0.6 m in width. The prefabricated element is 98% air by volume and has a density of 33.0 kg/m^3. The EPS has a characteristic short-term compressive strength equal to 250.0 kPa and long-term compressive strength equal to 75.0 kPa with a 2% strain, see Figure 4 a).

Figure 4 b) shows the prefabricated element made of EPS used as the strip foundation of a traditional wood-stud wall within mineral fiber insulation. When supporting a wood-stud wall, the insulation underneath the concrete floor slab can be of the same thickness throughout the concrete floor slab. The exterior wood-stud wall is supported by the concrete beam behind the outer plinth.

The prefabricated element of EPS was designed to form part of a foundation system that allows very little heat to be lost through the strip foundation, the joint between the ground deck and the exterior wall. The heat loss through the strip foundation will be referred to as the surplus heat loss, [W/mK] in the following. The surplus heat loss is defined as that heat loss which cannot be attributed to the one-dimensional heat loss through the ground deck and the exterior wall, individually. Surplus heat loss through the joint between the ground deck and the exterior wall is closely related to the design of the strip foundation.

Stainless steel rods of 5 mm in diameter were put through the EPS, every 0.6 m, forming the mechanical fastening point of the concrete for the outer plinth and the concrete floor slab. The mechanical fastening between the concrete for the outer plinth and the concrete floor slab contributes to the surplus heat loss through the strip foundation element. By using stainless steel rods, the contribution to the surplus heat loss is 0.002 W/mK (Danish Standards 2002, Table A.3.2). However, the contribution to the surplus heat loss decreases by using carbon fiber or other types of materials with a low coefficient of heat transmission to establish the mechanical fastening of the concrete for the outer plinth and the concrete floor slab.

The method calculating the surplus heat loss through the prefabricated strip foundation element is shown in Valdbjørn Rasmussen (2007 and 2008); a PC is used and the finite difference program HEAT2 version 5.0 in accordance with the method described in Danish Standards 2002. Calculations are dynamic with the outdoor temperature changing throughout the year.

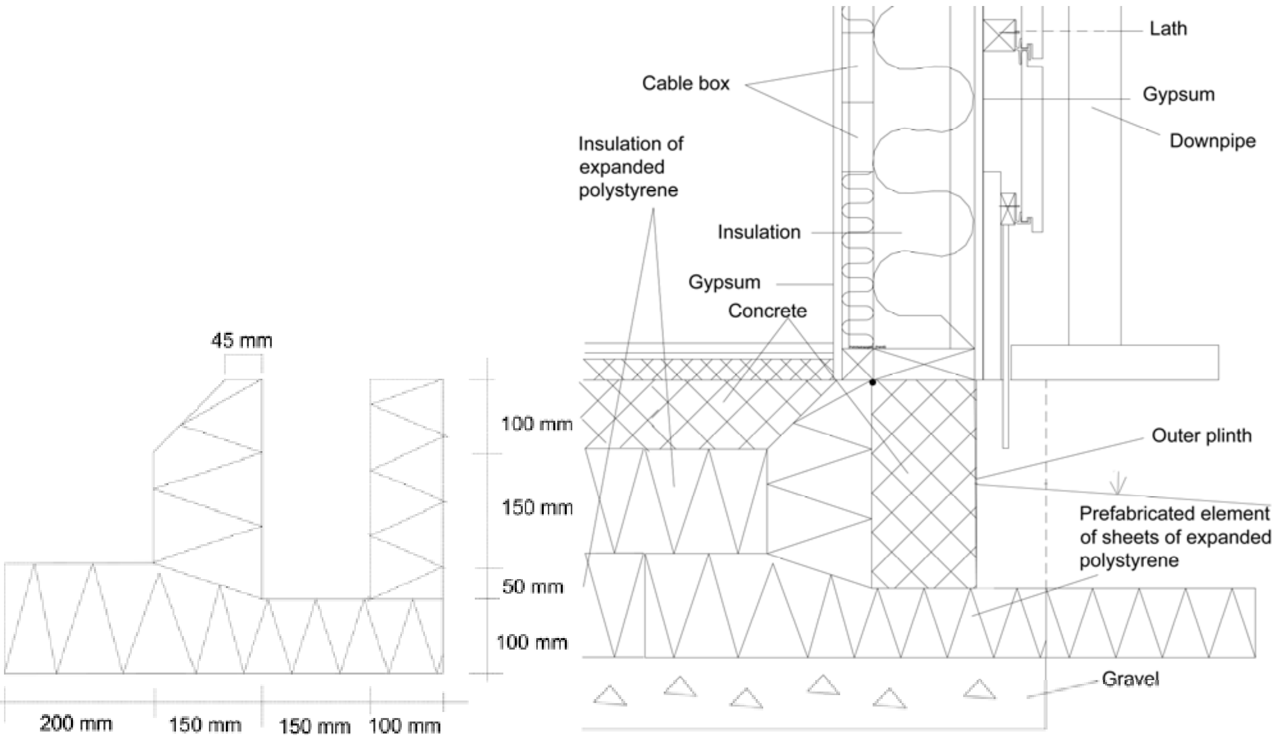

Figure 4 a): left, the prefabricated element made of EPS, b): right, the EPS element used as the strip foundation of a traditional wood-stud wall within mineral-based insulation.

2.2.2 Heat flow and temperatures in the strip-foundation system

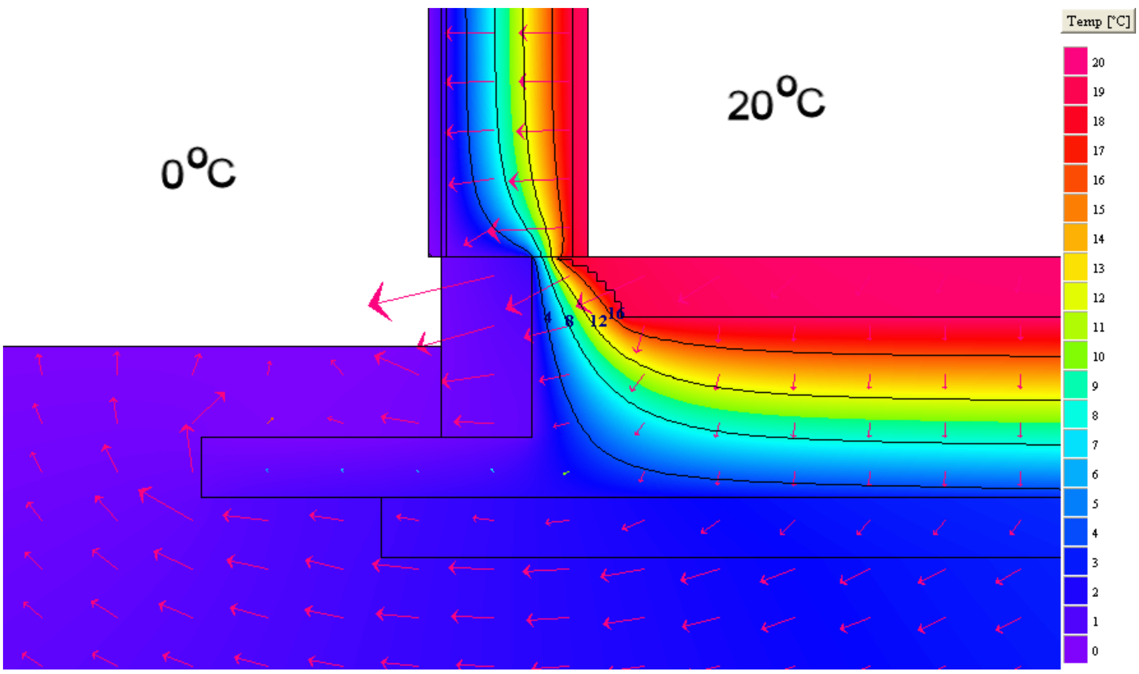

Figure 5. Temperature, isotherm curves and the heat flow through the prefabricated lightweight element used as strip foundation and the base for a traditional wood-stud exterior wall.

Ensuring stable non-freezing ground underneath the building was necessary for maintaining the stability of the structure and for avoiding settling cracks. To ensure stability of the strip foundation, it is important that temperatures lower than -1 °C do not occur in any frost-susceptible layer underneath the building during a cold winter (Danish Standards 2001). Temperatures below -1 °C underneath the capillary breaking layer could cause frost deformations of the soil underneath, which would in turn increase the risk of the strip foundation settling. Boards of EPS from the outer plinth of the strip foundation were used to form the element called the outer insulation. Design of the outer insulation was based on the descriptions given in the Danish Standards 2001, e.g. by using temperature characteristics for a cold winter, by using a design value of 100 years, where the lowest average outdoor temperature of a month decreases from -0.5 °C in a normal year to -7.3 °C in a cold year (Rose 2006).

Figure 5 shows the temperature, isotherm curves and the heat flow calculated for the prefabricated lightweight element, used as the strip foundation and the base for a traditional wood-stud wall within mineral fiber insulation. The average coefficient of heat transmission of the exterior wall was equal to 0.2 W/m^2K. For the calculations, the interim insulation to the ground deck and soil equaled 1.67 m^2K/W; the interim insulation to the soil itself equaled 1.5 m^2K/W, which allows the average coefficient of heat transmission of the ground deck to be 0.09 W/m^2K. Calculations were carried out with the specific heat capacity of the soil and the thermal conductivity of the soil set to 2.0 MJ/m^3K and 2.0 W/mK, respectively. Calculations were made for a building with conventional heating and for an outdoor temperature of 0 °C and an indoor temperature of 20 °C. The calculations were performed by using the PC program HEAT2 version 5.0 as a stationary calculation reaching thermal equilibrium between indoor and outdoor temperature. Arrows show the heat flow and the length of the arrows visualizes the relative heat flow. Isotherm curves are drawn as continuous lines with fixed indications of the temperature of the individual curve. Colors/grayscale used to visualize the temperatures are listed in the column to the right.

2.2.3 Building a strip foundation

Figure 6 a): Left, prefabricated leightweight elements, made of EPS, mounted as the strip foundation. The elemente were fixed together with large clamps of plastic, b): Right, 300 mm EPS, mounted as two layers on top of the base of stamped gravel bordered by the strip foundation that served as the insulation layer underneath the concrete floor slab. Iron was mounted as a net inside the strip foundation and as wires along the moat formed by the two vertical boards of EPS in the prefabricated elements, before concrete was cast and leveled.

At most locations in Denmark, a stable ground of glacial deposit (moraine) is present underneath a top soil layer of approximately 0.2 to 0.4 m in thickness. The top soil layer was removed in an area covering the area of the building. Material down to a depth of at least 0.35 m underneath the top soil surface had to be dug up. The excavated area was then covered with a capillary breaking layer of gravel, which was stamped in order to form the stable base for the building. The prefabricated EPS elements were mounted as the strip foundation, see Figure 6a). Fixed together with large clamps of plastic and with an outer support. 0.3 m of EPS in two layers, was mounted inside the strip foundation, served as insulation underneath the concrete floor slab. Before casting the concrete, an iron net was mounted to prevent cracks from developing due to shrinkage, inside the strip foundation and as wires along the moat formed by the two vertical boards of EPS in the prefabricated elements. Wires of stainless steel rods, 5 mm in diameter were put through the inner vertical boards of the prefabricated elements of EPS every 0.6 m, in order to connect the concrete in the moat to the concrete floor slab. Concrete was cast and leveled, see Figure 6b). After a few hours, when the concrete was dimensionally stable, the outer vertical boards of the prefabricated elements of EPS were removed, thus exposing the outer surface of the concrete moat as the outer plinth. The removed outer vertical boards of EPS were used as the outer insulation on the ground around the plinth.

3. Discussion

The tightened energy provisions included in the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008) are intended to result in an energy reduction of 25% for new buildings compared with buildings built in accordance with the former Building Regulations. By focusing on the air tightening of the building envelope, the heat transmission of the thermal envelope and thermal bridges that cause heat transmission through individual building components and joints, more sustainable buildings are constructed with reduced energy consumption for heating and comfort.

This study focuses on two specifically important areas for the heat loss through the building envelope, in particular methods to ensure air tightening of the building envelope and thermal bridges. Thermal bridges are prevented by introducing a new building component for the strip foundation, ensuring continuity of the thermal insulation layer in the exterior wall and the insulation underneath the concrete floor slab. Furthermore, the on-site performance of the superinsulated strip foundation of prefabricated lightweight elements was introduced and demonstrated as an alternative to the traditionally used strip foundation of concrete.

3.1 Air Tightening

Infiltration in the building envelope causes unnecessary heat loss and a risk of mould growth. The water vapor content in the outdoor air is low in winter. When the cold air enters the heated rooms indoors, it will be heated up and the relative humidity of the indoor air will decrease as a consequence (Andersen et al. 1993). The indoor air will be altered by water vapor generated by occupants, plants and everyday activities such as cooking and washing. In this case the air in a heated occupied room will contain more water vapor than the outdoor air. In winter, air that leaks out through unforeseen leakages in the building envelope will decrease in temperature and rise in relative humidity. The air is likely to condense within the insulation, thus increasing the moisture content and the risk of mould growth and the decomposition of the building. By building airtight and ventilate well and controlled through vents, moisture and polluted air can be removed from the indoor environment. A certain amount of air change is necessary to keep the relative humidity of the indoor air at an acceptably low level.

Infiltration in the building envelope can easily be prevented. An airtight shell that encases the heated interior of a building should be introduced at the design phase. Typically the shell follows the building envelope that consists of lightweight or heavy weight building components. Often lightweight wood-stud walls or heavy weight concrete wall elements are used mounted with windows, doors, ceiling, roof and ground constructions. Critical locations in the shell are located where building components are located in staggered levels in between building components and at ductways, where installations are brought into the building.

For some building components the airtight shell can with advantage be established by a polyethylene foil that also serves as the vapor barrier placed within the building envelope. The foil serving as the vapor barrier should be placed in the insulation located at the warm side of the dew point in order to avoid condensation. For the airtight shell it is important that the joints between building components are securely fixed. Furthermore it is crucial that the joints keep their airtight properties during the lifetime of the construction, and are not damaged or decompose during their service life. This entails a great deal of focus on how to establish the airtight shell on site as well as during the design phase.

3.2 Superinsulated Strip Foundations

The prefabricated element was designed to comply with requirements of low energy consumption for buildings by lowering the heat loss through the thermal envelope. The surplus heat loss through the foundation element, the joint between the exterior wall and the floor slab, was partly secured by the geometrical continuity of the thermal insulation layer across the joint and partly by the overall design of the element. The prefabricated lightweight foundation element was designed to be integrated into the insulation layer located underneath the concrete floor slab at the ground deck and to face the insulation within the exterior wall. At the bottom of the exterior wall, the heat flow increase significantly changed thermal resistance regarding the change in the thickness of the insulation material towards the exterior wall, see Figure 5. Hence the geothermal heat is used to ensure that there is stable, ground not susceptible to frost underneath the building. Therefore it was necessary, for maintaining structural stability and to prevent settling cracks during cold winters, to establish outer insulation in front of the outer plinth.

The investigation covered a real life situation and use of a newly designed element to be used as the strip foundation of a single-family house. The house was a single-storey house with an exterior wall made as a traditional wood-stud wall within insulation. The performance of the element was observed and recorded on site. Ground conditions at the building site consisted of a stable ground of glacial deposit (moraine) covered with a capillary break layer of gravel, stamped to obtain stable base for the building. The base for the house was cast in one working operation and completed within two working days. The elements were adjusted on site and shown to be able to be handled by one man.

4. Conclusion

Air tightness of building envelopes is a key factor in determining infiltration, heat loss, indoor air quality, maintainability and moisture balance within the building envelope as indoors. Air leakages through the building envelope contribute to the cost of ventilation, heating and cooling and also to moisture migration.

Furthermore, air tightness is that property of building envelopes which is the most important for understanding ventilation. Air tightness is important from a variety of perspectives mostly from infiltration, movement of air through leaks, cracks, or other and unforeseen openings in the building envelope. There is a direct connection between an airtight building envelope and low energy consumption for heating in the building. With regard to a better heat-insulated building envelope, the importance of an airtight building envelope becomes more pronounced in relation to the total energy consumption of the building. If using a heat exchanger for the ventilation system of the building to ensure fresh air to fulfill human needs for hygiene and comfort, a less efficient system is provided decreasing in efficiency with less efficient air tightness of the building envelope.

Thermal bridges, parts of the building envelope where the otherwise uniform thermal resistance is significantly changed, and effects on heat loss has been ignored for many years. Full or partial penetration of the building envelope by materials with a different thermal conductivity, by a change in thickness or discontinuation of the insulation material is traditionally found at window, door, wall, floor, and ceiling joints. Such thermal bridges give rise to two- or three-dimensional heat flows and have a major effect on the thermal performance of the building envelope. Furthermore, thermal bridges locally decrease the surface temperature indoors, thus increasing the risk of mould growth at high humidity levels. As for a better heat-insulated building envelope the importance of avoiding thermal bridges becomes more pronounced in relation to the total energy consumption of the building. The effect of thermal bridges in the building envelope is significant, either due to the long length of joints per unit of the heat loss surface or due to joints with large thermal transmittance. When eliminating thermal bridges in the building envelope, it is important to design joints as well as new building component that ensure continuity of the thermal insulation layer of the building envelope.

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